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GASSING OF PAPER WRAPPED CONDUCTORS

Report No 87-4-K

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ABSTRACT

Thirteen, 38 cm diameter disk winding models, 8 assembled with non-thermally-upgraded, power transformer winding insulation and 5 with upgraded (cyanoethylated) insulation, were subjected to thermal overloads under a variety of pressure, moisture content and electrical stress conditions. Short term gas emissions were >99% water vapour while long term (100 h) emissions also included CO₂, CO, H₂, CH₄ and C₂H₄. Wet insulation (6% moisture) degraded significantly in 100 hours at 150°C while dry insulation (<0.5% moisture) did not. The gassing onset temperature can be calculated from the system pressure and paper water content, and gassing rate data indicate that gradual rather than sudden overloading in field operations would minimize gassing and dry the windings.

job	file	date	report no.
32-212-533	832.771	January 8, 1988	87-4-K



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EXECUTIVE SUMMARY

GASSING OF PAPER WRAPPED CONDUCTORS

W.J. Janis

Gas generation in the vicinity of hot spots within paper wrapped transformer windings under load is recognized as a potential cause of electrical failure in transformers. Fault gases trapped in windings may reduce the dielectric strength of insulating oil and oil saturated paper insulation to below a value where an arcing short circuit can occur at relatively low levels of electrical stress.

During an emergency overload condition the effect of insulation moisture content on the gassing onset temperature, the effect of the hydrostatic head pressure in suppressing gassing, and the decrease in dielectric strength of the winding due to the presence of gas bubbles can become critically important factors affecting the performance of a transformer.

Experimental data is lacking in the above areas for winding materials and designs relevant to Ontario Hydro and the present work was undertaken at the request of the Transmission Stations Department, Transmission Operations Division, to increase our understanding of the overload condition.

Relatively large power transformer windings (38 cm diameter) of known paper type (standard or thermally upgraded) and known moisture content were overloaded under a variety of initial conditions. The following were noted: (1) high initial paper moisture content significantly accelerated the degradation of cellulose insulation at 150°C through the mechanisms of hydrolysis and oxidation; (2) the primary gas emission was water vapour, approximately 99% by volume, with the remainder air; (3) the gassing onset temperature could be related to the system pressure by empirical relations and gas law formulae; and (4) the pressure required to suppress gassing increased at a given hot spot temperature, but fell again as the stock of adsorbed water was depleted.

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The study indicates that conservator tank pressure does not assure protection against gassing, as the maximum pressure required to suppress gassing in a transformer can be higher than the static head pressure of most conservator tanks, especially if the insulation has a high water content and the transformer is suddenly overloaded. Further, because the rate of moisture buildup in the oil adjacent to the cellulose depends upon the thermal gradient, gradual loading of a transformer would minimize gassing by reducing the rate at which moisture is transferred to the adjacent oil layer, while leaving the process of moisture exchange between the adjacent oil layer and the bulk oil largely unaffected.

Further experimental work is recommended to: (1) elucidate the moisture migration mechanism in oil impregnated cellulose; (2) develop loading procedures which would minimize gassing effects and maximize loading rates; and (3) clarify if extremely dry transformers might have potential for high load service.



TABLE OF CONTENTS

	<u>Page</u>
1.0 INTRODUCTION	1
2.0 TEST CHAMBER AND WINDING MODELS	2
3.0 EXPERIMENTAL	3
3.1 Thermal Calibration	3
3.2 System Standards	4
3.3 Insulating Oil and Winding Model Conditioning	5
3.4 Winding Model Test Summary	5
4.0 RESULTS AND DISCUSSION	6
4.1 Winding Insulation Degradation Due to Aging at 150 °C	6
4.1.1 Dissolved Water and Gas Analysis	6
4.1.2 Winding Condition After Aging	7
4.2 Incipient Gas Emission Analysis	8
4.3 Dependence of Gassing Temperature on Winding Moisture Content and System Pressure	9
4.4 Dependence of Gassing Pressure On Time	15
4.5 Dielectric Breakdown Strength of Gassing Winding Models	15
5.0 CONCLUSIONS	17
6.0 RECOMMENDATIONS	18
REFERENCES	20
APPENDIX 1 Test System	21
APPENDIX 2 Disk Winding Model	26
APPENDIX 3 Thermal Calibration	29

TABLE OF CONTENTS (cont'd)

	<u>Page</u>
APPENDIX 4 Oil and Winding Model Conditioning	32
APPENDIX 5 Dielectric Breakdown Test Procedure	33
APPENDIX 6 Degree of Polymerization Test Procedure	34
APPENDIX 7 Temperature/Pressure Data-Gas Suppression Tests	35
APPENDIX 8 Gas Equilibria Calculations	40



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To: Mr. J.S. Hartill
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GASSING OF PAPER WRAPPED CONDUCTORS

1.0 INTRODUCTION

Gas generation in the vicinity of hot spots within paper wrapped transformer windings under load is recognized as a potential cause of electrical failure in transformers. Fault gases trapped in windings may reduce the dielectric strength of insulating oil and oil saturated paper insulation to below a value where an arcing short circuit can occur at relatively low levels of electrical stress.

A widely accepted method of minimizing the hazards of gas generation in paper wrapped windings is to set maximum temperature limits for the hottest spot of a conductor. These limits are based on experimental evidence of how quickly the paper insulation around the conductor degrades at various temperatures. Temperature limits set out in published loading guides of the Institute of Electronic and Electrical Engineers (IEEE)^{1,2/} recommend maximum hottest spot temperatures for 55°C and 65°C average winding rise insulation of 150°C and 180°C, respectively.

A major problem with the IEEE loading guide temperature limits is their dependence on a single long-term failure characteristic, insulation aging. This ignores the fact that short-term effects of sudden overloads such as gas bubble release from rapidly heating winding insulation can be more restrictive to loading practices than long-term concerns^{3/}.

The present work was undertaken at the request of the Transmission Stations Department, Transmission Operations Division, to increase understanding of gas generation in paper wrapped transformer windings under short-term and long-term thermal stresses^{4/}. Important considerations were: the effects of hydrostatic pressure and insulation moisture on bubble

formation; the influence of time lag in attaining gas generation temperatures and the electrical potential required to cause arcing when gas bubbles were present.

In the research program, 38 cm diameter, power transformer winding models of known paper type and moisture content were tested in a large, oil-filled enclosure. High current and high potential sources were connected to the test models at various times to produce thermal overload and/or high electrical stress conditions within the windings. Resulting effects, such as conductor gassing, oil or paper degradation or turn-to-turn arcing, were monitored and the data used to interpret fault severity.

Two types of winding insulation were used in this study, a standard 55°C winding rise paper insulation and a 65°C winding rise thermally upgraded (cyanoethylated) paper insulation.

2.0 TEST CHAMBER AND WINDING MODELS

A 135 L capacity, vacuum tight, stainless steel test chamber equipped with plexiglass viewing ports was used as an enclosure for winding models under test. Connected to the chamber were: (1) an oil circulation system consisting of a pump, flow meter and in-line oil heater; (2) a vacuum system and; (3) a dry air source. With this equipment the following operations were possible:

- (1) Vacuum drying of winding models prior to oil impregnation.
- (2) Oil impregnation of winding models under vacuum.
- (3) Oil degassification under vacuum.
- (4) Oil circulation at adjustable flow rate, either parallel or perpendicular to the axis of the winding model.
- (5) Saturation of test oil with dry air.
- (6) Pressurization of the chamber at pressures up to 100 kPa gauge.

Power cables, thermocouples and sampling lines entered the test chamber through O-ring sealed fittings mounted in the plexiglass windows. The complete test system and specifications are described in Appendix 1.

The winding models were constructed to resemble a portion of a transformer disk winding. As described in Appendix 2, the model consisted of two circular coils of insulated copper wire, separated by pressboard spacers and held together with twine or

cotton tape. The two coils were electrically connected to form a complete disk winding model consisting of two, parallel, 14-turn windings.

Fifteen winding models were prepared for this project by the Central Maintenance Shops, Pickering, following specifications established by the Transmission Stations Department. In nine models the copper conductor had a cross-section of 2.1 mm x 6.0 mm and was wrapped with four layers of standard cellulosic insulation. In the other six models the copper cross-section was 1.3 mm x 5.2 mm and the wrapping was ten layers of thermally upgraded (cyanoethylated) cellulosic insulation. In this report, these winding models are referred to as "4-paper" and "10-paper" winding models, respectively.

The total insulation thickness between adjacent turns was 0.61 mm for 4-paper models and 1.52 mm for 10-paper models.

The coil binding material for the first three winding models tested was cotton tape, a material commonly used to secure transformer leads and which has been used to bind coils in conductor models in other test programs/3/. However, the use of tape was discontinued after the first three tests to eliminate a potential source of moisture not generally found in operating transformers. The tape was replaced by twine in all other models.

3.0 EXPERIMENTAL

The experimental program consisted of testing the winding models under different operating conditions. The following were controlled variables: (1) initial water content of winding insulation and insulating oil; (2) initial dissolved air content of the insulating oil; (3) system pressure; (4) bulk oil temperature; (5) winding model hottest spot temperature; (6) rate of increase of winding model temperature (winding model time constant) and (7) insulation paper type.

Because of strong thermal convection currents in the oil and the geometry of the test chamber, the oil flow rate in the vicinity of the disk winding model was not controlled and increased with coil temperature.

3.1 Thermal Calibration

Thermal calibration tests were performed to determine the location and temperature of the hottest spot of the winding models as a function of winding current. This was necessary as thermocouples could not be used in tests where high voltages were applied to the winding models. In such tests, hottest spot temperatures were determined from the test current data and the thermal calibration curves.

One winding model of each type was sacrificed in the calibration procedure, leaving eight 4-paper and five 10-paper models for test.

In the calibration tests, thermocouples were mounted in the following locations:

- (1) Under cotton tape or twine, between turns 7 and 8, but not touching the bare copper conductor. (That is, with the insulating wrap of the conductor intact.)
- (2) Between a pressboard spacer and the upper disk, between turns 7 and 8, and touching the bare conductor. (That is, with the insulating wrap of the conductor pierced by the thermocouple.)
- (3) Touching a bare conductor, between turns 7 and 8 of the upper disk, no tape or twine near the thermocouple.
- (4) As in (3) but on the lower disk.

Thermocouple locations are shown on Figure 6 of Appendix 2. As expected, the thermocouple (2), above, registered the highest temperature in the calibration run because of the restricted oil flow in the vicinity of the spacers. Thermal calibration data is presented in Appendix 3.

3.2 System Standards

Because of the potentially large number of system variables in the thermal stress tests, it was necessary to choose a reference state for winding operation. The conditions adopted as standard are listed in Tables VII and VIII of Appendix 1, for 4-paper and 10-paper windings, respectively. The standard conditions were chosen to simulate the following service conditions:

- (1) Relatively little moisture in the windings or insulating oil.
- (2) Air saturated oil, as will be found in all transformers equipped with conservator tanks open to the atmosphere.
- (3) A short duration current overload which rapidly increases the winding temperature of a transformer normally operating to maintain an 80°C oil temperature against a 20°C ambient.

The heat rise profiles of Tables VII and VIII were defined by the test system response to an external current setting, selected to maintain the hottest spot of the winding model at 150°C and 180°C, for 4-paper and 10-paper winding models, respectively. The profiles represent a compromise between the desire for an instantaneous rise to a target hottest spot temperature and the

limitations imposed by the heat transport properties of the test system. The 150°C and 180°C hottest spot limits were chosen to coincide with the maximum hottest spot temperatures allowed under IEEE loading guides (Reference 1 and 2) for the two types of winding tested.

The hottest spot temperature had no standard value and was usually set slightly higher than the temperature required for incipient gas evolution from the winding model.

3.3 Insulating Oil and Winding Model Conditioning

To achieve the required <20 mg/kg water content and 0.08 L/L dry air content prior to each test, the test oil was degassed, using the test chamber as a vacuum degassifier, then saturated with dry air. To rid the air-saturated oil of any bubbles trapped under horizontal projections, the system was degassed for 15 min following the air saturation procedure, then brought to atmospheric pressure with dry air. Finally, the oil was circulated at 80°C for up to 48 h to complete the system conditioning.

The test winding model was placed in the chamber prior to oil entry and degassification, and was impregnated with oil under vacuum as the oil sprayed into, then filled, the test chamber.

While the above oil degassing procedure reduced the moisture content of the winding paper somewhat, moisture measurements for winding models subjected to vacuum and temperature conditions similar to those of the conditioning procedure showed that such losses were not significant. For example, to achieve 0.5 percent by weight paper moisture for windings three and four, 24 h heating in a vacuum oven at 115°C and 0.4 kPa pressure was required.

Details of the winding and oil conditioning procedures are given in Appendix 4.

3.4 Winding Model Test Summary

Experimental conditions used for the nine tests of 4-paper, non-thermally upgraded winding models and the five tests of 10-paper, cyanoethylated winding models are listed in Tables VII and VIII of Appendix 1, respectively. The test objectives were as follows:

(1) Four-Paper Winding Models 1 and 3

Long-term (100 h) stability of paper insulation to a 150°C hottest spot condition.

(2) Four-Paper Winding Model 2

The effect of pressure excursions at a relatively low hottest spot temperature, but high initial paper moisture content. (The pressure excursions mimic the effect of oil head pressure due to conservator tank placement.)

(3) Four-Paper Winding Models 4, 5, and 6,
and Ten-Paper Winding Models 10, 11, 12 and 13

The influence of temperature and pressure on the onset or stopping of gas evolution from low, medium and high initial moisture content paper.

(4) Four-Paper Winding Model 7

The dielectric breakdown resistance of high moisture content paper with air bubbles trapped between turns due to inadequate oil impregnation.

(5) Four-Paper Winding Models 8 and 9,
and Ten-Paper Winding Model 14

The dielectric breakdown resistance of high moisture content paper during the onset of gassing. Winding model 9 was the same as winding model 2, renumbered and reused following the mild and non-destructive winding model 2 test.

4.0 RESULTS AND DISCUSSION

4.1 Winding Insulation Degradation Due to Aging at 150°C

Two aging tests of four-paper winding models at a hottest-spot winding temperature of 150°C were carried out to determine the relative extent of winding insulation degradation of high and low moisture content paper, and the effect such degradation might have on the dissolved trace hydrocarbon gas content of the bulk insulating oil.

Winding models 3 and 1 were used in 100 h tests designated AT-1 and AT-2, respectively. Model 3 had an initial moisture content of 0.5 % by weight and model 1 had an initial moisture content of 6.0 % by weight. A test duration of 100 hours was chosen to exaggerate the effect of high temperature overload periods accumulated over the lifetime of a transformer to accent data trends, and it is acknowledged that such excessive service conditions do not exist in the Ontario Hydro transmission system.

4.1.1 Dissolved Water and Gas Analysis

Dissolved water, carbon dioxide, carbon monoxide, hydrogen, methane, ethane, ethylene and acetylene content of the bulk oil

were monitored at approximately 20 h intervals during the aging tests. The gas analysis results are summarized in Table I.

Except for ethylene in test AT-2, all the dissolved hydrocarbon gas concentrations increased approximately linearly with time during the aging tests. For ethylene, a sharper increase to an approximately constant value was noted during the first 20 h.

In both aging tests, the water content of the bulk oil increased to a nearly constant value within the first 20 h. Although the winding model in AT-2 had 12 times the initial water content of that used in AT-1, the water released to the bulk oil during AT-2 was only about 1.6 times that released during AT-1. This indicates possible retention of water by the paper insulation, or by oil close to the insulation, during aging at 150°C.

Gas emissions were expected from winding models in both tests due to paper degradation and, to a lesser extent, oil oxidation. More gassing was expected in Test AT-2 than in AT-1 because of a significantly larger amount of water available for cellulose hydrolysis, a mechanism which breaks bonds and weakens the cellulose structure. The data of Table I confirm the expectation of increased gas production in AT-2.

Carbon dioxide and carbon monoxide can be emitted by cellulose or oil degradation processes at 150°C in the presence of air/5-7/. Therefore, both oil and cellulose were potential gas generation sources in the aging tests, as the bulk oil was air saturated at the start of each test. The increased CO₂ and CO gas production noted in test AT-2 was probably aided by hydrolysis, which lowers the resistance of cellulose to oxidation in the presence of dissolved air.

4.1.2 Winding Condition After Aging

After approximately 100 h of aging at 150°C, the test windings were de-energized and subjected to 60 Hz, turn-to-turn electrical stress, following the method described in Appendix 5. The winding model of test AT-2 suffered dielectric failure at a stress of 7.4 kV/mm while the winding model of test AT-1 survived a sequence of applied stresses up to and including the 16.7 kV/mm limit of the test transformer.

When the winding model of test AT-2 was removed from the test chamber it was apparent that the cellulose insulation was severely charred and degraded, and bare copper was exposed in several spots due to the loss of charred and brittle insulation. In contrast, the winding model of test AT-1 was only somewhat discoloured during the test.

TABLE I
DISSOLVED WATER AND GAS DATA SUMMARY*
- WINDING AGING TEST AT 150°C

Test Duration (h)	Dissolved Gas Concentration ($\mu\text{L/L}$) **					
	CO_2		CO		H_2	
	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
0	900	2700	50	140	3	7
20	2600	4700	290	490	21	33
40	3700	6000	500	800	24	44
60	4800	7400	650	1180	30	54
80	5600	9000	860	1620	40	65
Average	3520	5960	470	846	24	41

Test Duration (h)	Dissolved Gas Concentration ($\mu\text{L/L}$)					
	CH_4		C_2H_4		Dissolved Water (mg/kg)	
	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
0	5	12	1	2	30	57
20	9	19	2	16	53	76
40	12	22	2	16	53	82
60	17	26	3	17	53	82
80	17	32	3	18	53	80
Average	12	22	2	14	48	75

* Test 1 = Winding model 3, 0.5 % moisture content insulation.
Test 2 = Winding model 1, 6.0 % moisture content insulation.
Acetylene (C_2H_2) was not detected in any test. Ethane (C_2H_6) was detected in both tests but could not be reliably quantified.

A degree of polymerization test was carried out on paper samples taken from the AT-2 winding before and after aging to determine the extent of cellulose degradation. As described in Appendix 6, this test showed the paper to be >85% degraded due to the 100 h aging process.

4.2 Incipient Gas Emission Analysis

Vigorous gassing of 4-paper winding models occurred when insulation containing 3-6 percent by weight moisture was heated to 130-150°C under the standard conditions of Table VII of

Appendix 1. However, similar insulation with less than 0.5 percent moisture gassed very little. This suggests that the gas generated when relatively wet windings are heated is mostly water vapour desorbed from the insulation. To confirm this, the standard winding model placement was altered to allow capture and analysis of a gas sample as discussed below.

To assure capture of desorbed gas, a winding model initially containing 3 percent by weight water (4-paper test model 6) was inclined in the test chamber so that thermally generated gases would rise along the inclined plane formed by the top half of the winding model and into a sampling line connected to a syringe.

Two successive oil samples were taken from the sampling line, one prior to and one just following the onset of vigorous gassing at 150°C. The second sample captured a gas bubble approximately 1 cm in diameter at 80°C and 37 kPa gauge pressure. However, the bubble disappeared when the oil sample was cooled to 20°C at 0 kPa gauge pressure. Dissolved gas data for the two oil samples is presented in Table II.

From the difference column of Table II, four components were identified as possible sources of the captured gas bubble: (1) nitrogen; (2) carbon monoxide; (3) carbon dioxide and; (4) water vapour. The maximum bubble volumes at 80°C and 37 kPa, gauge, for these gases are given in Table III.

From the gas bubble diameter data of Table III, it is clear that water vapour is the only candidate capable of producing a bubble as large as the 10 mm diameter one captured. In addition, nitrogen content was determined by subtracting other gas contents from the total dissolved gas and was therefore sensitive to errors in oxygen content. Total air content (nitrogen plus oxygen) had a gas difference of 1000 µL and a maximum bubble diameter of 1.13 mm. The captured bubble was therefore approximately 99.8 percent by volume water vapour and possibly 0.2 percent air. (eg, $100 \times (1.13/9.48)^3 = 0.2 \text{ vol-\%}$)

4.3 Dependence of Gassing Temperature on Winding Moisture Content and System Pressure

To study the dependence of gassing temperature on winding moisture content and system pressure, 4-paper winding models 2, 4, 5, 6, and 10-paper winding models 10-13 were heated at several different system pressures.

Because of the complexity of the test setup, it was not practical to change disk models after only one temperature excursion and therefore winding temperature and system pressure were varied many times during each test. This enabled several pressure/temperature points at which gassing commenced to be determined in each test - but with the introduction of

uncertainty in the paper water content and winding model condition.

System pressure and hottest spot temperature were usually alternately applied, with the overall effect being an excursion to higher temperature and pressure. Some excursions occasionally traced a closed path on a pressure/temperature grid to assess the significance of hysteresis, and all variations were kept as short as possible to minimize changes in the windings during test.

TABLE II
DISSOLVED GAS SAMPLES - WINDING MODEL 6

COMPONENT	SYRINGE SAMPLE		DIFFERENCE
	BEFORE GASSING	AFTER GASSING	
Hydrogen ($\mu\text{L/L}$)	<5	<5	0
Oxygen ($\mu\text{L/L}$)	24100	22300	-1800
Nitrogen ($\mu\text{L/L}$)	54500	57300	2800
Carbon Monoxide ($\mu\text{L/L}$)	<20	50	50 (max)
Methane ($\mu\text{L/L}$)	<2	<2	0
Carbon Dioxide ($\mu\text{L/L}$)	230	560	330
Ethylene ($\mu\text{L/L}$)	<2	<2	0
Ethane ($\mu\text{L/L}$)	<2	<2	0
Acetylene ($\mu\text{L/L}$)	<2	<2	0
Water (mg/kg)	27	39	12
Total Gas (%)	7.89	8.02	0.13

TABLE III
MAXIMUM BUBBLE SIZE DUE TO GAS DIFFERENCES OF TABLE II

GAS	OBSERVED DIFFERENCE ($\mu\text{L/L}$)	GAS IN SYRINGE* ($\mu\text{L/L}$)	GAS VOLUME AT STP** (μL)	GAS VOL. AT 80°C, 37 kPa (μL)	BUBBLE DIA. (mm)
Nitrogen	2800	6.72	6.72	6.12	2.26
Carbon Monoxide	50	0.120	0.12	0.11	0.60
Carbon Dioxide	330	0.792	0.79	0.72	1.12
Water Vapour	12 (mg/kg)	0.360 (mg)	490	446	9.48

* Total dissolved gas = 8 percent by vol., sample = 30 g (35 mL)
** STP = Standard Temperature and Pressure.

The temperature/pressure variations used in the tests are given in Appendix 7 and the experimental conditions required for incipient gassing, as determined from the data of Appendix 7, are given in Tables IV and V, for 4-paper and 10-paper models, respectively, and are discussed below.

As shown in Section 4.2, the gas generated when test windings are first heated is mostly water vapour, and in the calculations that follow it is assumed that gas emissions in the tests of this section were also predominantly water vapour.

In all tests, the temperature at which gassing occurred was above the pressure-corrected boiling point of water. This indicates that water released from the cellulose is dissolved in the oil within the winding and does not exist as a separate liquid or vapour phase upon release. If desorption of water occurs at a temperature above its boiling point, it must dissolve in the locally hot oil until its partial pressure exceeds the local pressure and it can be released as a gas bubble.

TABLE IV

CALCULATED NON-EQUILIBRIUM WATER CONTENT OF OIL
REQUIRED FOR GASSING AT OBSERVED GASSING
TEMPERATURES AND PRESSURES FOR FOUR-PAPER WINDING MODELS

TEST	PAPER WATER CONTENT (WT-%)	CONDITIONS FOR INCIPIENT GASSING		CALCULATED WATER CONTENT OF OIL REQUIRED TO CAUSE GASSING (WT-%)
		TEMPERATURE (°C)	PRESSURE (kPaG)	
2	5	135	14	3.9
2	5	145	60	4.2
2	5	130	5	4.3
5A	5	142	44	4.1
6A	3	143	36	3.6
6A	3	145	38	3.4
5B	2.5	141	0	2.5
6B	2.5	143	7	2.6
4	1	156	0	1.5

TABLE V

CALCULATED NON-EQUILIBRIUM WATER CONTENT OF OIL
REQUIRED FOR GASSING AT OBSERVED GASSING
TEMPERATURES AND PRESSURES FOR TEN-PAPER WINDING MODELS

TEST	PAPER WATER CONTENT (WT-%)	CONDITIONS FOR INCIPIENT GASSING		CALCULATED WATER CONTENT OF OIL REQUIRED TO CAUSE GASSING (WT-%)
		TEMPERATURE (°C)	PRESSURE (kPaG)	
12	6.0	150	28	2.5
10	3.5	148	0	2.0
10	3.5	156	23	2.0
11	3.0	153	0	1.7
13	0.5	>190	0	<0.1

As a starting point, the partial pressure of the water vapour can be calculated by using Henry's Law:

$$P = P^{\circ}X \quad [1]$$

where P is the partial pressure of water vapour, P° is the vapour pressure of pure water at the test temperature, and X is the mole fraction of water in the oil.

Because the partial pressure of the oil is quite low at all test temperatures, it can be ignored for the purposes of calculation, and the condition for gas release from the oil is therefore:

$$P^{\circ}X > P_{\text{total}} \quad [2]$$

where P_{total} is the absolute test system pressure.

Using [2], the concentration of water which must be exceeded to produce gassing in oil immediately adjacent to the hottest spot cellulose can be calculated as:

$$X = P_{\text{total}}/P^{\circ} \quad [3]$$

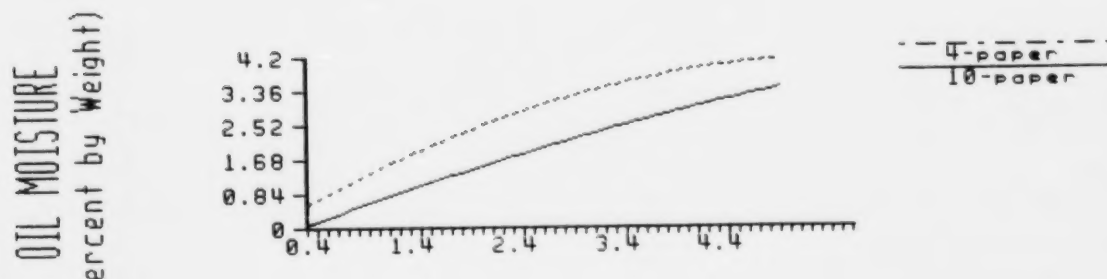
The above application of Henry's law to the non-equilibrium situation existing within oil impregnated cellulose is intended as an empirical extension only, as a treatment of the complex interaction of thermal and moisture gradients, capillary effects and adsorption/desorption phenomena in layered cellulose structures are beyond the scope of this investigation. However, as discussed below, empirical relationships can be useful in estimating gassing onset temperatures from paper moisture content data.

Dissolved water in oil content calculations are discussed in Appendix 8 and the results are presented in the right-most columns of Tables IV and V for 4-paper and 10-paper winding models, respectively.

As detailed in Appendix 8, the oil and paper water content data of Tables IV and V can be related adequately by empirical relationships in which the water content of the oil, W_O , is expressed as a quadratic function of the water content of the paper, W_P , for each winding model type. Plots of W_O versus W_P are shown in Figure 1 for 4-paper and 10-paper models.

FIGURE 1

NON-EQUILIBRIUM OIL MOISTURE IN THE VICINITY
OF A HOT SPOT AS A FUNCTION OF
INSULATING PAPER MOISTURE CONTENT



The standard deviations of the quadratics plotted in Figure 1 are 0.26 and 0.84, approximately, for 4-paper and 10-paper data, respectively. The statistical data are presented in Appendix 8.

If the total system pressure is known, the empirical curves of Figure 1 and the following equations [4] and [5], derived in Appendix 8, can be used to estimate the gassing onset temperature from paper moisture content:

$$X = W_O / (6.92 + 0.93 * W_O) \quad [4]$$

$$T = 247 / (1 - (1/19.65) * \log_e(7.4793 * P_{total} / X)) - 273 \quad [5]$$

where T is the gassing temperature in $^{\circ}\text{C}$, P_{total} is the system pressure in kPa, X and W_O are as defined above and $*$ denotes multiplication.

For example, a 4-paper winding model having a paper water content of 5 percent by weight and at a system pressure of 161 kPa (60 kPa gauge) would have the following values for W_0 , X , and T :

$$W_0 = 4.14 \text{ (from Figure 2, or Appendix 8)} \quad [6]$$

$$X = 4.14 / (6.92 + 0.93 * 4.14) = 0.384 \quad [7]$$

$$T = 247 / (1 - (1/19.65) * \log_e(7.4793 * 161 / 0.384)) - 273 = 145^\circ\text{C} \quad [8]$$

The value of T calculated by equation [8] is the same as that observed in 4-paper test 2, Table IV.

The utility of equations [4] and [5] depends upon a knowledge of the moisture content of operating windings. For a system in thermal equilibrium, it is often possible to relate the moisture content of the oil to the moisture content of the paper by means of published curves. For example, Reference 8 provides data relating bulk oil water content, in terms of percent saturation, with paper water content at two oil temperatures, 20°C and 80°C . If an appropriate working curve is available, then it is possible to approximate the expected gassing temperature using equations [4] and [5], and the W_0 value obtained from the paper water content estimate, calculated from published curves and experimental dissolved water in oil data. The errors involved in such a procedure are not clear and further experimental work appears necessary in this area.

4.4 Dependence of Gassing Pressure on Time

In the short duration tests of Section 4.3, incipient gassing at constant temperature could be suppressed by slightly increasing the system pressure. However, the gas suppression was temporary, about 20 s, at constant pressure, and successive pressure increases were required to stop gas evolution at a constant hottest spot temperature. Gassing was suppressed in this manner during 4-paper test 8 and 10-paper test 12, until it was noted that the gassing remained stopped at constant pressure. After this point, the pressure required to stop gassing decreased with time.

The pressure required to suppress gassing is plotted in Figure 2, where it is noted that for both tests the maximum pressure was achieved in about the same time, 15 minutes.

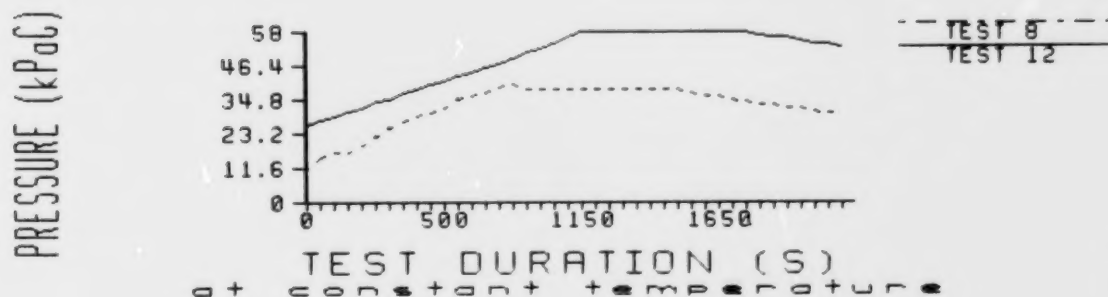
According to the arguments of section 4.3, the increase in system pressure required for the suppression of gassing in Tests 8 and 12 was due to an increase in the water content of the oil in the vicinity of the hottest spot cellulose. Therefore, the pressure increases observed in Figure 2 indicate migration of water into the oil surrounding the coil, at a rate faster than it can be removed by convection and diffusive forces. The pressure

decreases observed at the end of the tests indicate the loss of most of the water of adsorption and the consequent drying of the winding models.

As expected, the adsorbed water in winding insulation is mobile under the influence of a sufficient thermal gradient, and this suggests that winding conditioning under sustained, moderate load would be beneficial in removing excess water that might lead to gassing under a high loading condition.

FIGURE 2

SYSTEM PRESSURE REQUIRED TO SUPPRESS GASSING
4-PAPER TEST 8 AND 10-PAPER TEST 12



4.5 Dielectric Breakdown Strength of Gassing Winding Models

To determine the effect of gas generation on the electrical resistance of winding model insulation, 4-paper test winding models 7, 8 and 9, and 10-paper winding model 14 were subjected to 60 Hz, turn-to-turn electrical stress while under load.

The test procedure is described in Appendix 5 and the data is given in Table VI, below.

The early failure of winding model 7 was due to the presence of air bubbles trapped in this winding model as a consequence of improper conditioning. (Air bubbles were observed to be trapped on the underside of some horizontal surfaces of the winding model

before the failure). The 7.2 kV/mm failure stress is therefore approximately the free-air dielectric breakdown resistance of the 4-paper winding model.

For winding models 8 and 9, turn-to-turn failure was coincident with the onset of gassing caused by a pressure reduction at 135°C in the presence of a 7.2 kV/mm electric field. It is noted that no damage to these coils was caused by a 7.2 kV/mm field when the winding models were not gassing, and model 9 survived a 16.0 kV/mm stress in the absence of gassing. The gas generated during these tests appears to have lowered the dielectric strength of the winding model to approximately the free-air value obtained with winding model 7.

TABLE VI
DIELECTRIC STRESS TEST DATA

Winding	Event Number	Hottest Spot Temperature (°C)	Gassing Observed	Field (kV/mm)	Dielectric Breakdown Observed
7	1	85	No	7.2	Yes
8	1	85	No*	16.0	No
8	2	135	No	7.2	No
8	3	135	Yes	7.2	Yes
9	1	85	No*	16.0	No
9	2	135	No*	7.2	No
9	3	135	No	3.2	No
9	4	135	Yes*	3.2	No
9	5	135	No	6.4	No
9	6	135	Yes*	6.4	No
9	7	135	No	7.2	No
9	8	135	Yes	7.2	Yes
14	1	165	No*	1.6	No
14	2	165	No*	3.3	No
14	3	165	No*	4.9	No
14	4	190	Yes	1.6	No
14	5	190	Yes	3.3	No
14	6	190	Yes*	4.9	No
14	7	165	No*	6.6	No
14	8	165	No	8.2	No
14	9	190	Yes	6.6	Yes

* At a system pressure of 45 kPa, gauge.

Winding model 14 showed similar behaviour to that of models 8 and 9, that is, it survived higher stresses when gassing was absent than when it was present.

The Table VI results indicate that considerable stress can be applied to a gassing winding without failure but that the breakdown resistance is probably not much better than the free-air value.

It was noted by Transmission Stations personnel that the stresses causing failure in this test program are considerably higher than those that occur in transformers in normal service at Ontario Hydro.

5.0 CONCLUSIONS

1. The gases CO_2 , CO , H_2 , and CH_4 were emitted from dry (0.5 percent by weight) and wet (6.0 percent by weight) winding cellulose at approximately constant rates during long-term aging at 150°C . Water and C_2H_4 emission rates were initially high, but decreased to negligible values after 40 h and 20 h of aging, respectively.
2. High initial paper moisture content significantly accelerated the degradation of cellulose insulation at 150°C through the mechanisms of hydrolysis, and oxidation by dissolved air. An insulating paper containing 6 percent by weight moisture was severely degraded in less than 100 h at 150°C , a period far short of the 250 h IEEE aging limit of Reference 1 for dry paper.
3. Analysis of bubble emissions from a gassing winding model show that the primary gas emission is water vapour, approximately 99 percent by volume. The balance of the emission is air.
4. The approximate initial gassing temperature of a winding model can be calculated from the initial system pressure and moisture content data using empirical relations, and standard gas law formulae governing the release of water vapour from oil. The oil taking part in the gas bubble generation is adjacent to the cellulose contributing the water and is mostly within the winding model itself.
5. The pressure required to suppress gassing of winding models, which are releasing adsorbed water at temperatures above the gassing onset temperature, increases approximately linearly with time, and eventually drops again as the stock of adsorbed water is depleted. The rate of the gassing suppression pressure increase in the winding model tests was approximately 2.5 kPa/min.

6. Conservator tank pressure does not assure protection against gassing as the maximum pressure required to suppress gassing in a transformer can be higher than the static head pressure of most conservator tanks, especially if the insulation has a high water content and the transformer is suddenly overloaded.
7. Because the rate of moisture buildup in the oil adjacent to the cellulose depends upon the thermal gradient, gradual loading of a transformer would minimize gassing by reducing the rate at which moisture is transferred to the adjacent oil layer, while leaving the process of moisture exchange between the adjacent oil layer and the bulk oil largely unaffected.

6.0 RECOMMENDATIONS

1. Further experimental work is recommended to elucidate the moisture migration mechanism in oil impregnated cellulose and to develop loading procedures which would minimize gassing effects and maximize loading rates. Quantitative relationships between bulk oil and winding moisture contents should also be determined for windings under steady load.
2. Because the 100 h aging test of dry insulation at 150°C did not significantly degrade the test winding model, long term (200-300 h) high temperature aging tests of very dry winding models are recommended to determine the expected life of such materials. Such tests would simulate transformer operation at above standard loading guide limits and would clarify if extremely dry transformers might have potential for continued high load service.

Approved by:



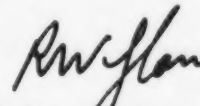
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W.J. Janis
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Materials Chemistry Section

Reviewed By:



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Supervising Chemist
Materials Chemistry Section

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APPENDIX 1

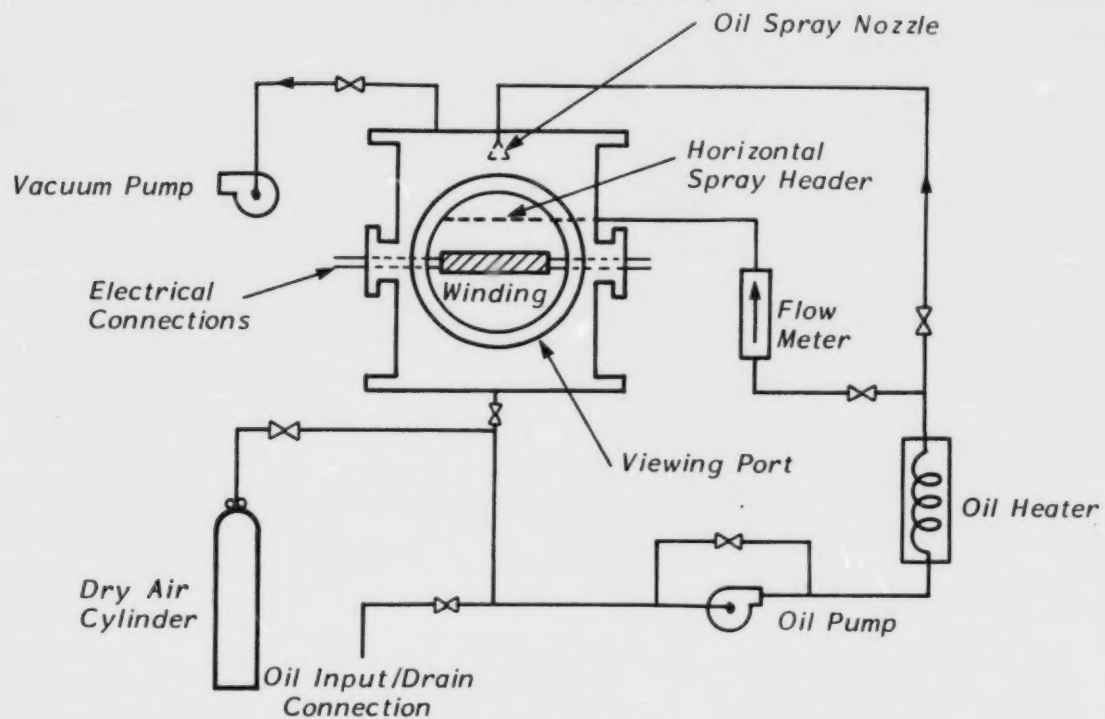
TEST SYSTEM

Schematic and electrical line diagrams for the test system are presented in Figure 3, and the system is shown in operation in Figure 4. Some specifications follow :

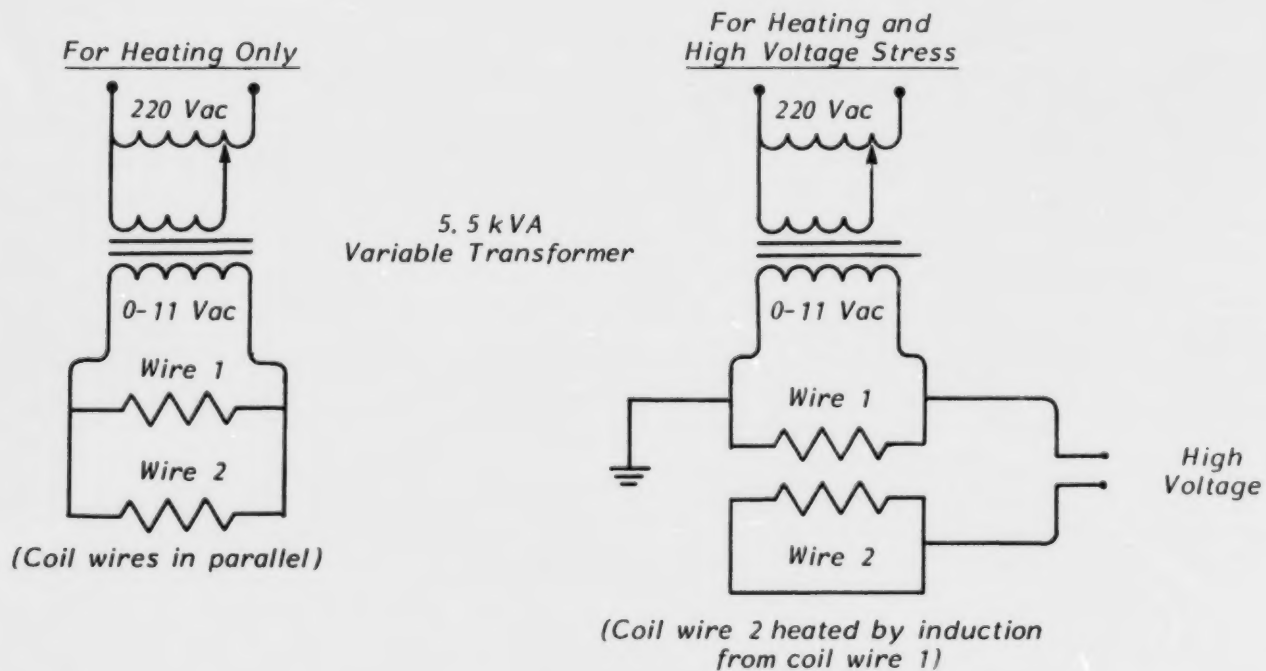
1. Pressure: 100 kPa maximum.
2. Vacuum: -101.3246 kPa, (3 micron) minimum.
3. Oil Temperature: 100°C maximum top oil temperature.
20°C minimum.
4. Oil circulation rate: 6 L/min., maximum.
5. Chamber volume: 135 L (125 L oil, 10 L dry air cushion).
6. Oil piping volume: 5 L (oil-filled).
7. Viewports: (a) Top, front and back - 40.5 cm diameter.
(b) Both sides - 15 cm diameter.
8. Chamber external dimensions (Maximum): -76 cm height
-76 cm length
-50 cm width.

The standard and experimental conditions used in the 4-paper and 10-paper tests are presented in Tables VII and VIII of this Appendix, respectively.

APPENDIX 1 (CONT'D)



(A) GASSING TEST SYSTEM SCHEMATIC



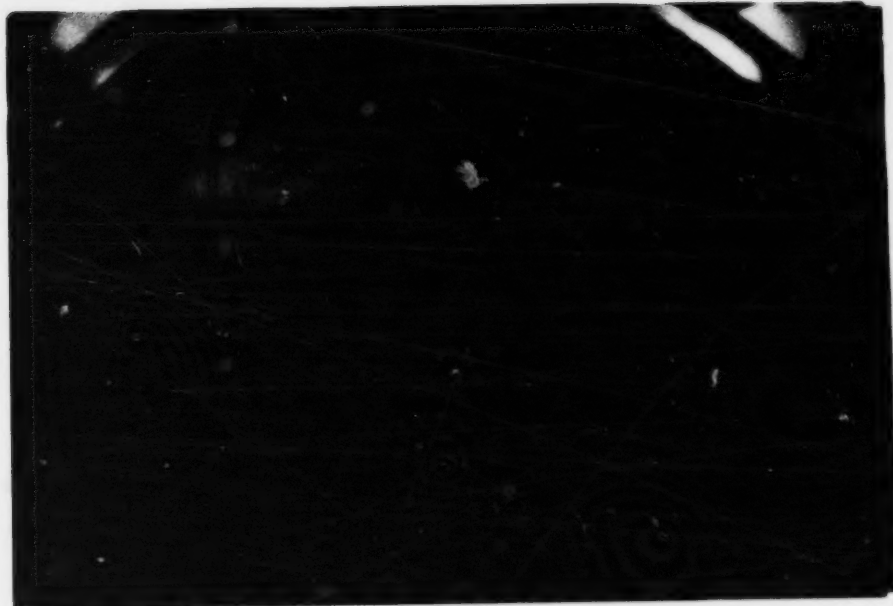
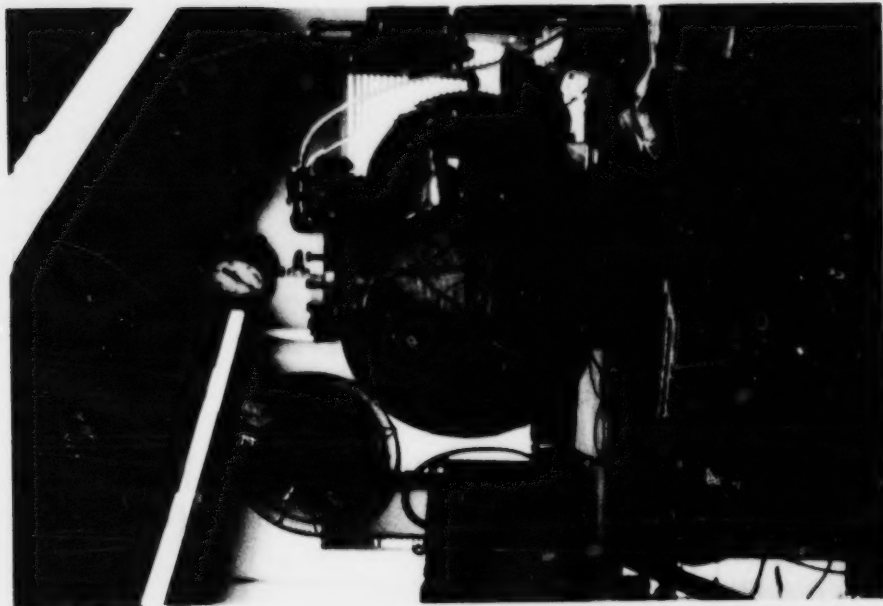
(B) ELECTRICAL CONNECTIONS - GASSING TEST SYSTEM

FIGURE 3

APPENDIX 1 CONTINUED

FIGURE 4

TEST SYSTEM PHOTOGRAPHS



APPENDIX I (CONTINUED)

TABLE VII

WINDING MODEL TEST RANGES FOUR PAPER WINDING MODEL*

VARIABLE	STANDARD VALUE	(EXPERIMENTAL VALUE (BY TEST NUMBER))								
		1	2	3	4	5	6	7	8 & 9	
Paper moisture (wt-%)	0.5-1.0	6.0	5.0	Standard	Standard	5.0	3.0	5.0	5.0	
Oil Moisture (mg/kg)	10-20	45	Standard	45	Standard	Standard	Standard	Standard	Standard	
Oil Air Content (L/L)	0.08	Standard	Standard	Standard	Standard	Standard	Standard	Standard	Standard	
Bulk Oil Temp. (Deg C)	80	Standard	Standard	Standard	Standard	Standard	Standard	Standard	Standard	
Hot Spot Temp. (Deg. C)	-	150	135	150	130-150	130-150	130-160	85	135	
Ambient Temp. (Deg. C)	22	Standard	Standard	Standard	Standard	Standard	Standard	Standard	Standard	
Hot Spot Temp. Rise (Deg. C/min)										
For 80-130 Deg. C:	40	Standard	Standard	Standard	15	15	15	No	Standard	
For 130-140 Deg. C:	10	Standard	Standard	Standard	Standard	Standard	Standard	Heat	Standard	
For 140-160 Deg. C:	2	Standard	Standard	Standard	Variable	Variable	Variable	Rise	Standard	
Hot Spot Duration (min.)	5	110 h	Standard	100 h	60 h	Standard	Standard	Standard	Standard	
System Pressure (kPa-g)	0	Standard	0-45	Standard	0-30	0-70	0-45	Standard	0-45	
Electrical Stress (kV/mm) (In 1.6 kV/mm/min Steps)	0	7.4	Standard	16	Standard	Standard	Standard	7.2	7.2	

* Non-Thermally upgraded.

APPENDIX I (CONTINUED)

TABLE VIII

WINDING MODEL TEST RANGES TEN PAPER WINDING MODEL*

VARIABLE	STANDARD VALUE	(EXPERIMENTAL VALUE (BY TEST NUMBER))			
		10	11	12	13
Paper moisture (wt-%)	0.5-1.0	3.5	3.0	6.0	6.0
Oil Moisture (mg/kg)	10-20	Standard	Standard	Standard	Standard
Oil Air Content (L/L)	0.08	Standard	Standard	Standard	Standard
Bulk Oil Temp. (Deg C)	80	Standard	Standard	Standard	Standard
Hot Spot Temp. (Deg. C)	-	150-180	150-180	150-180	150-180
Ambient Temp. (Deg. C)	22	Standard	Standard	Standard	Standard
Hot Spot Temp. Rise (Deg. C/min)					
For 80-130 Deg. C:	40	Standard	Standard	Standard	15
For 130-160 Deg. C:	10	Standard	Standard	Standard	Standard
For 160-180 Deg. C:	2	Standard	Standard	Standard	Variable
Hot Spot Duration (min.)	5	Standard	Standard	Standard	Standard
System Pressure (kPa-g)	28	0-45	0-55	0-70	0-55
Electrical Stress (kV/mm) (In 1.6 kV/mm/min Steps)	0	Standard	Standard	Standard	7.9

* Thermally upgraded.

APPENDIX 2

DISK WINDING MODEL

The coils which make up the winding model were formed by winding two rectangular, paper covered conductors in parallel onto a 30.5 cm diameter mandrel. Two coils of seven turns each were wound as a continuous disk winding with the start and finish leads on the outside and the crossover from disk to disk on the inside. Pressboard spacers were used to separate the disks.

A cross-section of a winding model is shown in Figure 5 and thermocouple placement is shown in Figure 6.

APPENDIX 2 (CONT'D)

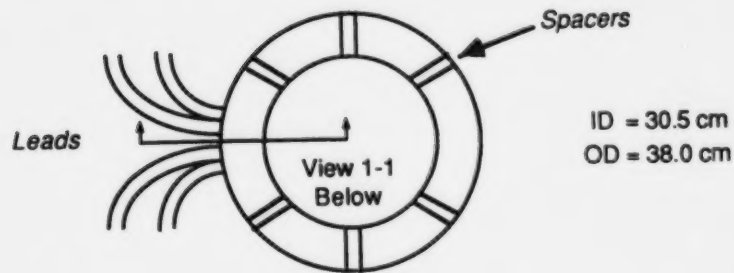


Figure 5(a) Top View

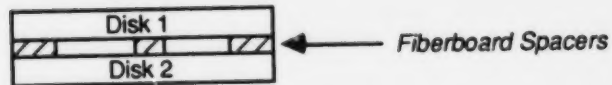


Figure 5(b) Side View

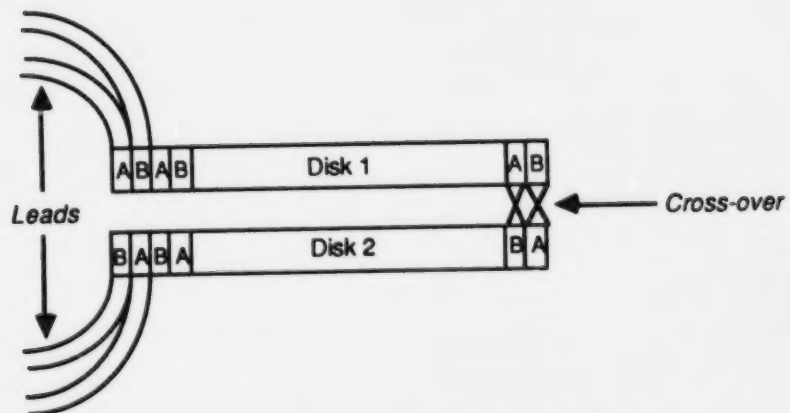
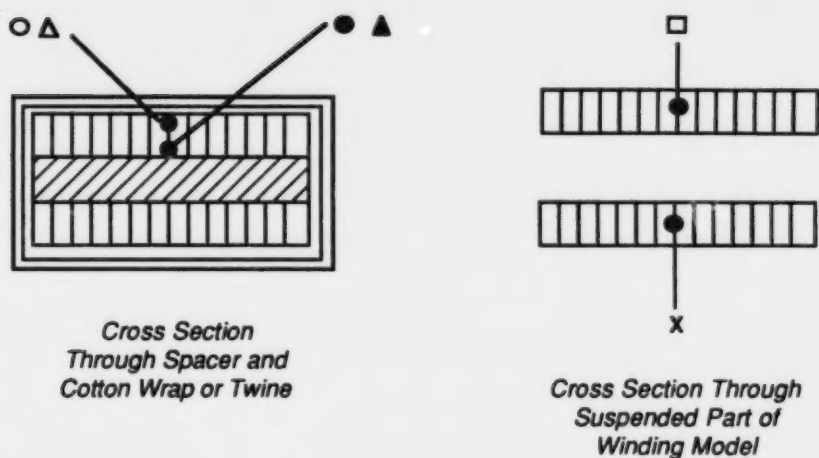


Figure 5(c) View 1-1 (enlarged)

FIGURE 5 WINDING MODEL

CHUCK DISK1
175997 RD

APPENDIX 2 (CONT'D)



- *Touching bare conductor, thermocouple inserted between pressboard spacer and turns 7-8 of uppermost coil - cotton taped winding model.*
- ▲ *As in 1 but for twine-wrapped winding model.*
- *On conductor between turns 7-8 of top coil - no tape or twine present.*
- X *As in 3 but thermocouple placed on bottom coil.*
- Δ *Under twine wrapping, between turns 7-8 but not touching bare conductor.*
- *As in 5 but under cotton tape.*

FIGURE 6
THERMOCOUPLE PLACEMENT

APPENDIX 3

THERMAL CALIBRATION

The following steps were performed to determine the temperature/current relationships, shown in Tables IX and X, for non-thermally-upgraded and thermally-upgraded winding models, respectively:

1. The test winding was fitted with thermocouples at the locations indicated in Figure 6 and placed in the test chamber.
2. The conditioning procedure of Appendix 4 was used to impregnate the winding with oil and to stabilize the system temperature at 80-85°C.
3. Winding model current was set using an ammeter and was held constant until thermocouple readings stabilized - about 15 minutes.
4. Winding model current was reset at successively higher values until a hottest spot temperature of 150°C or 180°C, depending upon model type, was exceeded.

TABLE IX

TEMPERATURE/CURRENT RELATIONSHIPS- 4-PAPER MODEL

Winding Current (Amperes)	Thermocouple Temperature ($^{\circ}\text{C}$) (By Thermocouple Number*)			
	1	2	3	4
100	108	104	104	100
110	110	105	106	100
120	114	107	109	100
130	118	110	112	101
140	123	114	116	102
150	129	119	120	105
160	135	124	124	109
170	142	130	129	114
180	150	138	134	119
190	159	145	140	125
200	168	154	146	133
210	178	164	152	141
220	189	175	159	150

- * TC 1 = On bare copper, under spacer, on top coil.
 TC 2 = On bare copper, not under spacer, on top coil.
 TC 3 = On bare copper, not under spacer, on bottom coil.
 TC 4 = On paper, top coil.

TABLE X

TEMPERATURE/CURRENT RELATIONSHIPS- 10-PAPER MODEL

Winding Current (Amperes)	Thermocouple Temperature ($^{\circ}\text{C}$) (By Thermocouple Number)			
	1	2	3	4
150	101	94	97	96
160	109	98	103	99
170	117	103	108	103
180	125	107	114	107
190	133	112	120	111
200	141	116	125	115
210	149	122	131	119
220	156	127	136	123
230	163	132	142	127
240	170	138	147	131
250	178	144	153	135
260	184	150	158	139
270	191	156	164	143

- * TC 1 = On bare copper, under spacer, on top coil.
 TC 2 = On bare copper, not under spacer, on top coil.
 TC 3 = On bare copper, not under spacer, on bottom coil.
 TC 4 = On paper, top coil.

APPENDIX 4

OIL AND WINDING MODEL CONDITIONING

Most test windings were dried following the procedure discussed in Reference 5, page 259, that is, heating the winding with current to 80-115°C, under vacuum, for 1-2 hours. However, it was noted that uniform drying to 0.5% moisture content was achieved only after prolonged heating (24 h), because the winding leads were significantly cooler than the 115°C winding hottest spot and did not lose trace adsorbed moisture readily under the system conditions.

The initial water contents of the winding models were measured gravimetrically from 10 g (approx) paper samples removed from the windings under a blanket of dry air. The water contents of windings prior to a second thermal excursion were calculated from the initial value, minus the amount released to the bulk oil as a result of the initial thermal excursion.

The following procedure was used to remove dissolved gases from insulating oil prior to use, and to saturate the oil with dry air:

1. Oil was drawn into the test chamber and circulation piping by vacuum.
2. As the oil entered the test system, it flowed through an 85°C, in-line oil heater, then entered the test chamber through a nozzle located at the top of the chamber. The nozzle dispersed the oil into a fine spray in the head space of the chamber to aid vacuum extraction of dissolved gases during the oil filling operation.
3. When the chamber was approximately two-thirds full, oil input was halted for 15 minutes to establish a 0.4 kPa vacuum. During this period the oil was continuously circulated through the heater and spray nozzle.
4. The filling procedure was re-established until a 12 L headspace remained at the top of the chamber, at which time the input was stopped.
5. The insulating oil was again cycled under full vacuum for one to four hours at 80-85°C to complete the degassing step.
6. Dry air was bubbled through the oil for 15 minutes at a rate of 0.75 L/min. following the degassing step to saturate the oil with dry air.

APPENDIX 4 cont'd

7. Following step 6, the vacuum pump was turned on for 15 minutes to remove trace air bubbles. This step was necessary because the air saturation procedure left dry air bubbles trapped under horizontal projections in the winding model. The applied vacuum was not high and the full 15 minutes was required to remove the last traces of free air at ambient pressure.
8. The oil was circulated for up to 48 hours prior to a test to condition the winding model.

APPENDIX 5

DIELECTRIC BREAKDOWN TEST PROCEDURE

The following procedure was used to determine the breakdown strength of winding insulation exposed to turn-to-turn electric stress :

1. The two wires of the winding model were disconnected from the power source and rewired in the configuration shown in Figure 3(B) of Appendix 1. That is, the ends of one wire were joined together to form an isolated loop, and the ends of the wire were connected to a grounded power supply.
2. A variable 60 Hz, high voltage supply was connected to the two wires of the winding model so that the electrical potential of the isolated loop could be raised to a maximum of 10 kV, relative to the grounded wire and power supply.
3. The temperature of the winding model was adjusted to the desired test temperature by controlling the current to the non-isolated winding. Because of the large inductive coupling between the two wires of the winding, and their close proximity, the temperature of the isolated wire was within 5°C of the temperature of the non-isolated wire.
4. Electrical stress was applied in 1 kV increments and, following McNutt of Reference 3, each level of stress was held for 1 minute. Turn-to-turn failure was indicated by a rapid loss of high voltage stress and a coincident arc or gas stream evolution at some point on the test winding.

In high temperature tests the above was carried out under pressure to prevent gas bubble release until a desired stress level had been established. At this point, the pressure was released and gassing occurred in the presence of the electric field.

APPENDIX 6

DEGREE OF POLYMERIZATION TEST PROCEDURE

The degree of polymerization of winding paper samples was calculated from intrinsic viscosity measurements of chemically digested samples following the method of References 9 and 10. A weighed sample of material is dissolved in a 0.5 M cupriethylenediamine hydroxide solution; then the viscosity of the solution, and also that of the solvent, are determined at 25°C by means of a calibrated glass capillary-type viscometer. The relative viscosity is determined and converted to intrinsic viscosity.

The cupriethylene solution was prepared according to the method of Reference 9 and standardized by a method detailed in Reference 8. Calculation of the degree of polymerization was aided by empirical tables of Reference 10 which related relative viscosity to intrinsic viscosity and intrinsic viscosity to degree of polymerization.

APPENDIX 7

TABLE XI

TEMPERATURE/PRESSURE DATA - GAS SUPPRESSION TESTS

(SEE APPENDIX 1, TABLES VII AND VIII, FOR HEATING RATES)

(a) Four-Paper Winding Model 2 (5.0% moisture content)

	Temperature (°C)	Pressure (kPa, gauge)	Gassing
Excursion 1	85	0	None
	130	0	Started
	130	28	Stopped
	130	56	None
	145	56	Started
	145	67	Stopped
Excursion 2	85	0	None
	130	0	Started
	130	11	Stopped

(b) Four-Paper Winding Model 4 (1.0% moisture content)

	Temperature (°C)	Pressure (kPa, gauge)	Gassing
	85	0	None
	120	0	None
	130	0	None
	150	0	None
	162	0	Started
	162	28	Stopped
	162	14	Started
	162	0	Continued
	150	0	Stopped

APPENDIX 7 CONTINUED

(c) Four-Paper Winding Model 5 (5.0% moisture content, Excursion 1; 2.5% moisture content, Excursion 2)*

	Temperature (°C)	Pressure (kPa, gauge)	Gassing
Excursion 1	85	35	None
	125	35	None
	130	35	None
	135	35	None
	140	35	Started
	143	35	Continued
	143	50	Stopped
	143	42	Started
	143	44	Stopped
	144	44	Started
	144	50	Stopped
	146	50	Started
	146	53	Stopped
	147	53	Started
	150	53	Continued
	150	67	Stopped
Excursion 2	85	0	None
	140	0	Started
	141	0	Stopped

(d) Four-Paper Winding Model 6 (3.0% moisture content, Excursion 1; 2.5% moisture content, Excursion 2)

	Temperature (°C)	Pressure (kPa, gauge)	Gassing
Excursion 1	85	0	None
	130	0	None
	143	0	Started
	143	35	Continued
	143	37	Stopped
	145	37	Started

* Moisture content for excursion 2 was calculated by subtracting the change in water content of the bulk oil during excursion 1 from the initial paper moisture quantity.

APPENDIX 7 CONTINUED

(e) Four Paper Winding Model 6 (continued)

	Temperature (°C)	Pressure (kPa, gauge)	Gassing
Excursion 2	120	0	Stopped
	150	0	Started
	150	14	Stopped
	150	4	Started
	150	25	Stopped
	163	25	None
	165	25	Started
	165	41	Stopped
	161	41	None
	161	28	Started

(f) Ten-Paper Winding Model 10 (3.5% moisture content)

	Temperature (°C)	Pressure (kPa, gauge)	Gassing
	85	0	None
	105	0	None
	124	0	None
	130	0	None
	140	0	None
	148	0	Started
	157	31	Stopped
	157	24	Started
	156	24	Stopped
	156	23	Started
	156	0	Continued
	180	0	Continued
	180	21	Stopped (30 s)
	180	21	Started
	180	28	Continued
	180	33	Stopped

APPENDIX 7 CONTINUED

(g) Ten-Paper Winding Model 12 (6.0% moisture content)

	Temperature (°C)	Pressure (kPa, gauge)	Gassing
Excursion 1	85	0	None
	130	28	None
	145	28	None
	155	28	Started
	165	28	Continued
	175	28	Continued
	175	42	Stopped
	175	0	Started
	175	28	Stopped (30 s)
	175	28	Started
	175	42	Stopped
Excursion 2	175	28	Started

(See Figure 2 of text for continuation at a constant temperature of 175°C)

(h) Ten-Paper Winding Model 11 (3.0% moisture content)

	Temperature (°C)	Pressure (kPa, gauge)	Gassing
Excursion 1	85	0	None
	105	0	None
	124	0	None
	130	0	None
	140	0	None
	148	0	None
	153	0	Started
	157	28	Continued
	166	28	Continued
	166	35	Continued
	180	35	Continued
	180	42	Stopped (30 s)
	180	42	Started
	180	49	Stopped (30 s)
	180	49	Started
	180	55	Stopped
Excursion 2	85	0	None
	130	0	None
	140	0	None
	150	0	None
	160	0	None
	170	0	Started

APPENDIX 7 CONTINUED

(i) Ten-Paper Winding Model 13 (0.5% moisture content)

	Temperature (°C)	Pressure (kPa, gauge)	Gassing
Excursion 1	85	56	None
	105	56	None
	115	56	None
	125	56	None
	135	56	None
	145	56	None
	155	56	None
	165	56	None
Excursion 2	85	28	None
	105	28	None
	125	28	None
	145	28	None
	165	28	None
Excursion 3	85	0	None
	105	0	None
	125	0	None
	145	0	None
	165	0	None

Appendix 8

GAS EQUILIBRIA CALCULATIONS

1.0 Calculation of Oil Water Content

As shown in the text, the mole fraction of dissolved water required to give gassing in the oil in the immediate vicinity of the cellulose is given by:

$$X = P_{\text{total}}/P^{\circ} \quad [8.1]$$

The vapour pressure of water, P° , is logarithmically dependent on temperature and follows the approximate relationship:

$$\log_e (P^{\circ} * 7.4793) = -4854.65/T + 19.65 \quad [8.2]$$

where T is the temperature in degrees Kelvin, P° is measured in kPa and * denotes multiplication /11/.

Therefore, the mole fraction, X, may be calculated from the system pressure and temperature using [8.1] and [8.2]. For example, if gassing occurs at 145°C and 60 kPa (gauge), then, from [8.2] :

$$\log_e (P^{\circ} * 7.4793) = -4854.65/(145+273) = 19.65 = 8.036005$$

or:

$$P^{\circ} = \text{EXP}(8.036005)/7.4793 = 413.1726$$

Therefore, from [8.1], the mole fraction, X, must be:

$$X = (60 + 101.3)/413.1726 = \underline{0.390}$$

The mole fraction data can be converted to weight-percent by use of the following formula:

$$WO/100 = M_1 X / [M_2 (1-X) + M_1 X] \quad [8.3]$$

where M_1 and M_2 are the molecular weights of water and insulating oil, respectively, and WO is the water content of the oil in percent by weight.

The average molecular weight for the insulating oil used in this study may be approximated as 260 gram-atom /12,13,15/. Substituting this value for M_2 , and the value 18 gram-atom for the molecular weight of water, M_1 , in [8.3] yields:

$$WO = 6.92X / (1 - 0.93X) \quad [8.4]$$

Equations [8.1], [8.2] and [8.4] were used to calculate mole fractions and weight-percent water contents from the equilibrium pressures and temperatures determined in the gassing tests and presented in Tables IV and V of Section 4.3.

If relation [8.2] is solved for T, and the value of P^0 of [8.1] substituted in this new relation, the following is obtained:

$$T = 247 / (1 - (1/19.65) \log_e (7.4793 * P_{\text{total}} / X)) - 273 \quad [8.5]$$

This is the equation [5] of the text.

2. Curve Fitting: Water-in-Oil Data fit to Water-in-Paper Data

The weight-percent water content of insulating paper was used as the independent variable in a least-squares fit of paper and oil water contents. A function of the form: $WO = C0 + C1*WP + C2*WP^2$, where $C0$, $C1$ and $C2$ are constants and WO and WP are the moisture contents of oil and paper, respectively, was used for the fitting procedure. The data used for the fits, and the resulting values of $C0$, $C1$ and $C2$, are given in the tables below.

2.1 Four-Paper Winding Models

Least-squares Function: $WO = 0.031541 + 1.4374*WP - 0.1233*WP^2$

Point Number	Raw Data		Calculated Data	
	(WP)	(WO)	(WO)	(WO minus observed)
1	0.0	0.0	0.0315	0.0315
2	1.0	1.5	1.3457	-0.1543
3	2.5	2.5	2.8545	0.3546
4	2.5	2.6	2.8545	0.2546
5	3.0	3.4	3.2342	-0.1658
6	3.0	3.6	3.2342	0.0315
7	5.0	4.1	4.1363	-0.1543
8	5.0	4.3	4.1363	0.3546
9	5.0	4.2	4.1363	0.2546
10	5.0	3.9	4.1363	-0.1658

¹ See, for example, Reference 14

2.2 Ten-Paper Winding Models

Least-squares Function: $WO = -0.2896 + 0.94583*WP - 0.04021*WP^2$

Point Number	Raw Data		Calculated Data	
	(WP)	(WO)	(WO)	(WO minus observed)
1	0.0	0.0	-0.290	-0.290
2	0.5	0.1	0.1732	0.0732
3	3.0	1.7	2.1859	0.4859
4	3.5	2.0	2.5281	0.5281
5	3.5	2.0	2.5281	0.5281
6	6.0	2.5	3.9376	1.4376